Getting a High-Quality Continuous Electricity Supply from a Mixed Solar and Wind Power System

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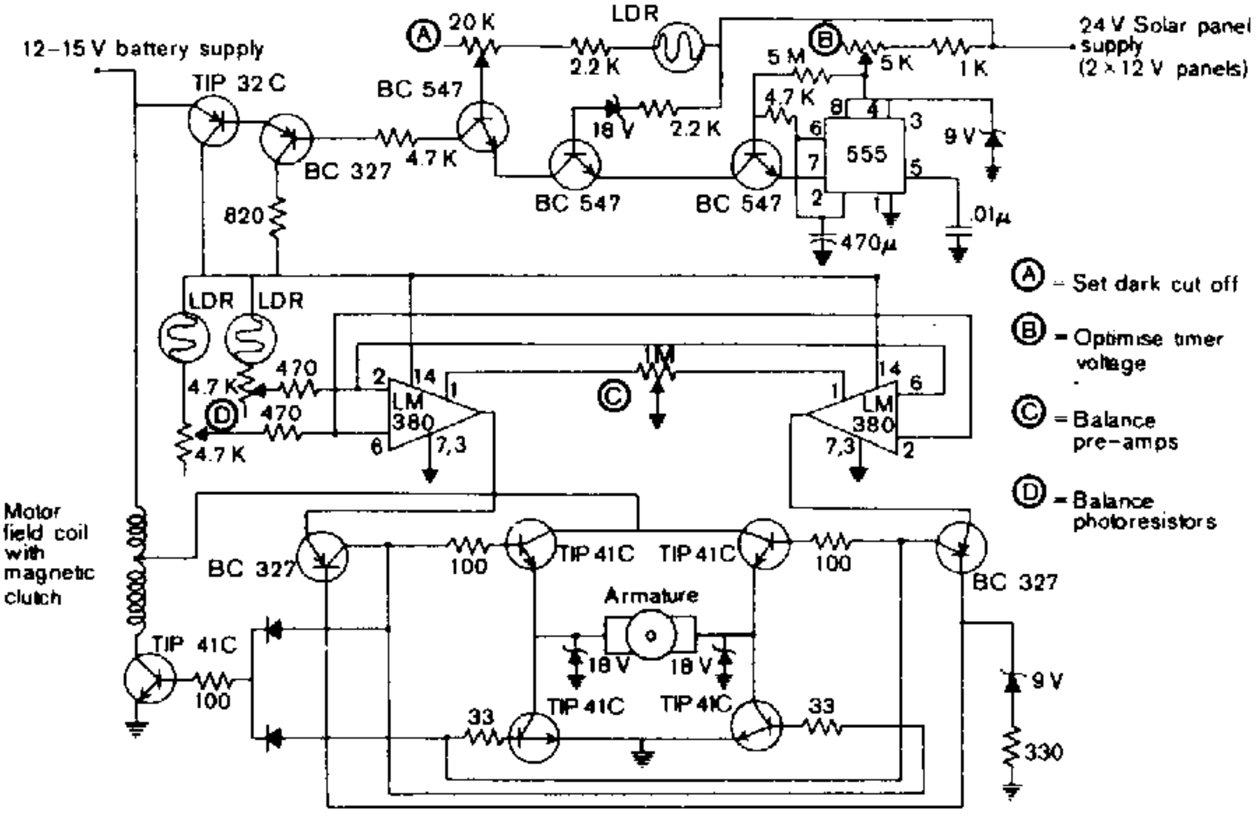
Background:
One of the key purposes of a national electricity grid is to provide continuity of power supply to the public, through the capacity to generate power reliably on demand. This is generally achieved with zero net electrical storage by the use of a combination of hydro-electric, gas or oil fired, nuclear, solar, wind or other systems, which are activated both as a function of demand and selectively in relation to the fluctuating power output of each type of generating system. The multiple 3-blade wind turbines at Altamont Pass and the 6 MW, 799 unit array of tracking 8-panel solar collectors at Carissa Plains in California (see cover of Solar Progress, Summer 1989) illustrate the use of multiple wind and tracking solar units in this context.

When designing remote area power systems (RAPS), attention has tended to concentrate on one type of natural power generation to the exclusion of others, often with the use of non-renewable internal combustion generators for backup. For example a large wind generator may be used with significant and expensive storage batteries, and a diesel generator for backup. Another favourite with distributors of solar power systems is to use fixed panels and motor generator backup. While these systems do provide continuity of supply, they are essentially reneging on the agenda of renewable energy to the extent that they are actually non-renewable fossil fuel burners for 15% to 35% of their output, making them comparable with public reticulation systems in terms of dependence on fossil fuels.



The obvious solution to this half-way step towards renewable energy is to develop multi-source remote area power systems, which provide continuity and reliability of supply with little or no reliance on fossil-burning generators. In particular, by combining wind and solar power generation, a low-cost system can be developed for remote domestic applications which has superior continuity of supply, periods of energy surplus which can be utilized for high-demand activities such as machine tools, and much better battery life, because of less direct demand on storage and superior recharging. Broadly speaking, the wind supply provides a more intermittent but higher-output source which provides ample power for heavier activities, while the solar supply provides a more steady input, maintaining more regular activities such as lighting, the use of T.V. computers and stereos etc. Shifting patterns of solar and wind energy also tend to complement one-another, with for example sunny windless highs being followed by possibly cloudy higher velocity air streams. This means that one system is often active when the other is quiescent, cutting the demand on batteries or fossil-plants to fill the gaps.

Plate 1 : The SOMA 500W windmill on a high steel pole.

Such enhancements can be augmented by improving the characteristics of solar power generation through the use of a low-cost tracking installation carrying 2 to 4 solar panels. This provides higher peak output through lateral mirrors, but more importantly gives a much broader, flatter peak through following the sun, enabling the use of peak-level solar power for a considerable proportion of the day (see fig 1). Many distributors of solar panels contend to their buyers that fixed solar panels are the most cost effective installation, partly to sell more panels. Some of the applications of solar technology in industry, such as telecommunications boosters, are to specific, low-demand, high-reliability applications, which justify the near-zero maintenance of fixed panels. However once an internal combustion backup is included, a fundamental revision of the maintenance aspect and the cost-efficiencies of single-source natural power systems has to be made. Once an auxiliary power system is included with a solar system, the low-maintenance logic goes out the window and cost-efficiency favours a tracking system, rather then fixed panels, since a well-designed tracking system has lower maintenance than an internal-combustion generator. The Carissa Plains tracking array also makes nonsense of the idea that fixed panels are necessarily the best compromise.

An example of a combined wind and tracking solar system is described in this article along with data demonstrating the enhanced performance characteristics and the design for a low-cost tracking assembly which can carry 2 to 4 panels. This was built in a typical remote site on coastal reserve land in which a high priority was having a system which was fully renewable, did not involve noise and environmental pollution from generators, and did not require regular refuelling and the associated running costs. On the other side I was determined to get a system on which I could depend as a professional person, so that I could, for example, write an article on computer without having to stop because I had exceeded the available supply. The idea of having to fire up an internal combustion engine to sit at a computer keyboard in such a natural power spot was out of the question.

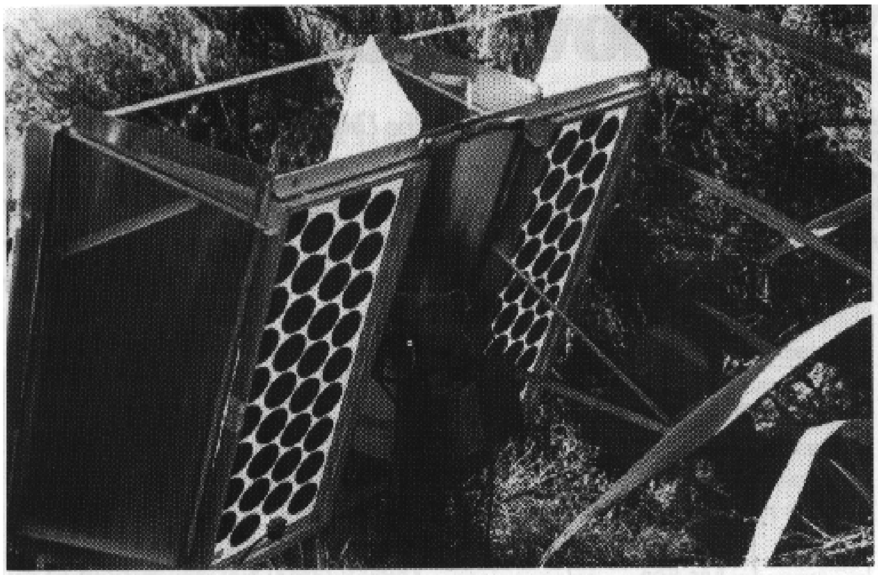
The Wind Generator :

The wind generator I purchased was a SOMA power 500W 24V model, plate 1 & fig 6. This has many highly desirable characteristics which I regard as essential. The first is that it will give significant charge in light winds. Many designs of windmill fail to do this and consequently have even more intermittent output than necessary. It has three adjustable pitch blades, which provide very good regulation of over run in high winds, with little noise pollution or vibrational strain. The 24 pole 3-phase permanent-magnet alternator, eliminates need for gearing and has little tendency to lock up magnetically. The windmill thus freewheels aerodynamically in light winds, coming into charge readily and giving steady high power in strong gusts. SOMA have since changed their design to a 300W 12 pole model with counter-weighted yawing regulation, which their specifications indicate has similar low wind sensitivity. The previous design is excellent but was more costly to produce. Their current design is also superior to competing models in wider distribution which could undercut the market for an excellent product - a serious flaw in the entire history of renewable energy! 24V is advantageous because of reduced rectification losses.

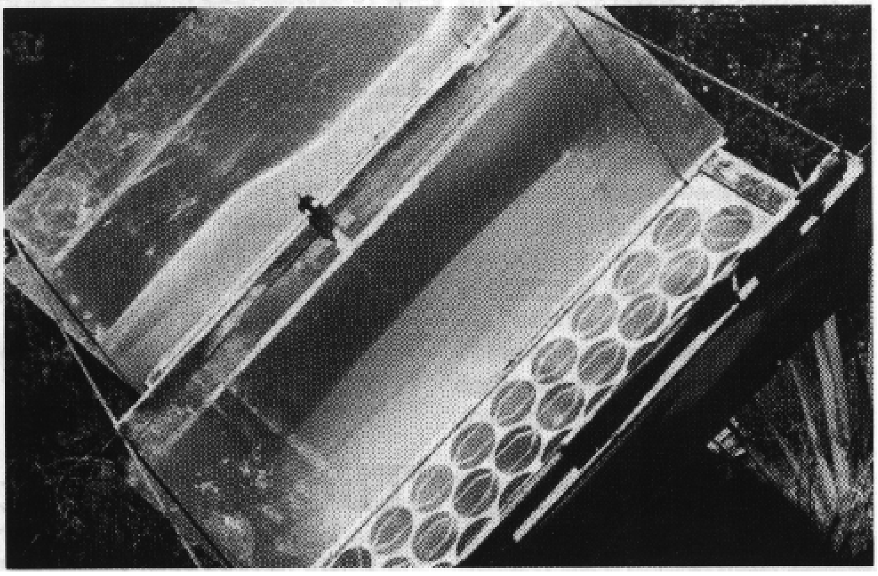
The windmill is sited on a 10m steel pole on a knoll overlooking the sea, 300m from the house. The high pole has contributed to the performance. It has adjustable guy wires and welded steps which make any maintenance vastly more straightforward. The site is exposed to high winds from most directions, but misses the southwesterly due to an obstructing ridge. I have the windmill adjusted to regulate its speed a little low so that it can run free in a gale instead of having to lock the tail. This made it possible for me to leave the system running during week long absences over several years without serious breakdown.

The Low-cost Tracking Solar Installation :

The tracking solar installation was my own design, see fig 6 and plates 2 to 5. Built in 1985, it predated the Carissa Plains installation and represents optimization for low-cost while providing an essentially similar unit. It has lateral reflectors which double the collecting area and boost the peak performance by approximately 50%. Glancing reflection off the panels and higher temperature losses contribute the difference. The backs of the panels ventilate freely and the undersides of the wafers are outlined mat black to improve radiative cooling. There is little reabsorbtion from the ground. The aluminium reflector and panel assembly has a counterweight so that the assembly is fullybalanced and will pivot without load. The whole assembly can be manually tilted to keep the track in line with the changing seasons.



Plates 2 & 3: Two views of the tracking solar assembly showing reflectors, cells painted mat black behind for cooling, counterweight, motor drive and sensors.



For simplicity the motor chosen was a Peugeot 504 windscreen wiper motor which has rotary action geared-down to about 60 r.p.m. and a magnetic brake, which locks the armature against a section of the core when power is removed. This is essential to prevent the entire assembly being blown out of line by gusts of wind. I rewired the brush assembly to isolate it from the field windings, so that reverse polarization of the armature reverses the drive direction. This is connected to the panel assembly by a bicycle chain and sprocket set. Both the mechanical and structural aspects of the design are thus very low cost in terms of parts and could be built cheaply in kitset form.

At the same time, I designed a simple electronic circuit which combines sensors and timers with a pair of competing amplifiers to provide the sun-seeking mechanism. The principles of this are straightforward and it is easy to build from the circuit diagram of fig 2. A 555 timer is set to turn the system on for 3 seconds each half-hour. This requires a large capacitor (470 µF) charged through a high resistance (1.5-5 MΩ). The input to the 555 is modulated through a sensor which prevents vagrant tracking in moonlight or twilight, and an 18V zener which senses the panels have power to give. In practice the latter is all that is required. When activated for 3 seconds, the two light-dependent resistors (LDRs) provide competing crossed inputs into the LM380 op. amps. which feed TIP41C transistors and hence the armature of the motor. The LDRs have a dividing projection to ensure accurate seeking plate 2. The LDRs should not be shorted through the 4.7 kΩ pots being set too low. A digital timer and counter chip could alternatively be used to time the intervals, but I have found the circuit reliable in all weathers when kept in a sealed box and smeared with a little Vasilene round the timer. The control box contains two 3-position switches which can manually operate the assembly. One has timer-off-on and the other has left-seek-right by bypassing the LDRs. These are useful in testing its operation.

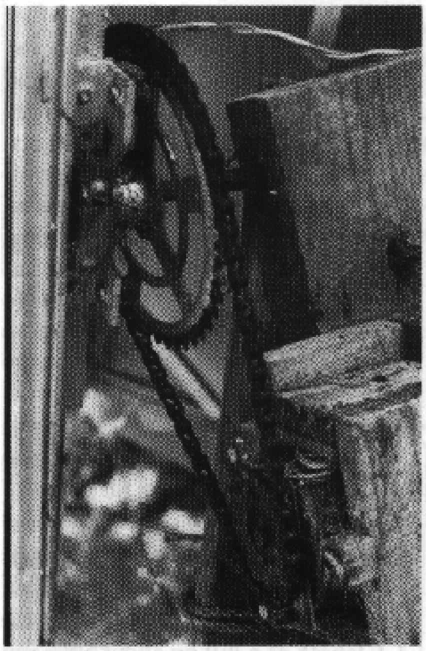


Plate 4:* *The chain drive assembly using geared down chain drive and a Peugeot windscreen wiper motor.

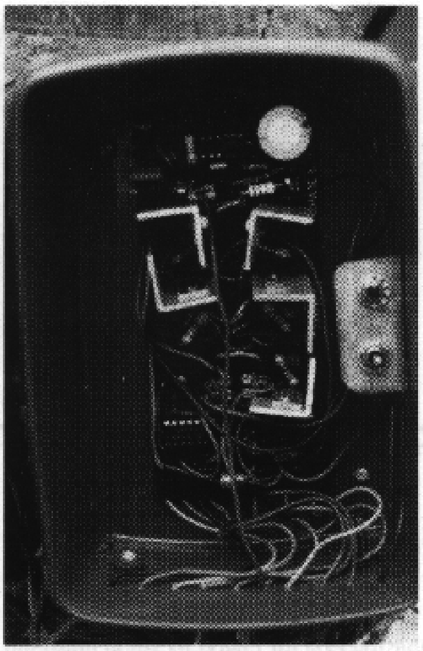


Plate 5:* *A view of the controlling circuit in its weather prrof housing.

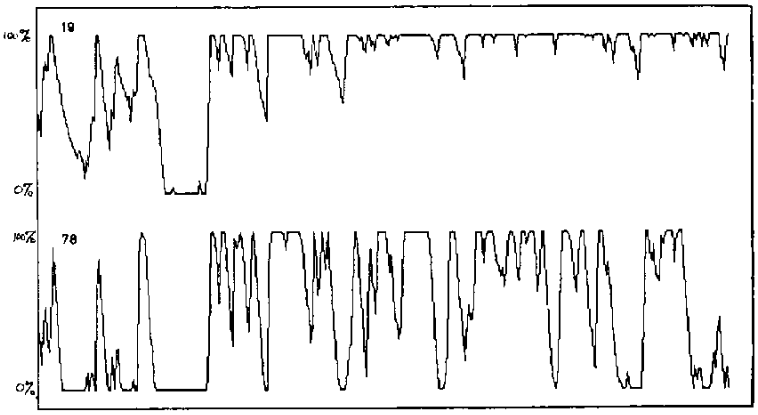
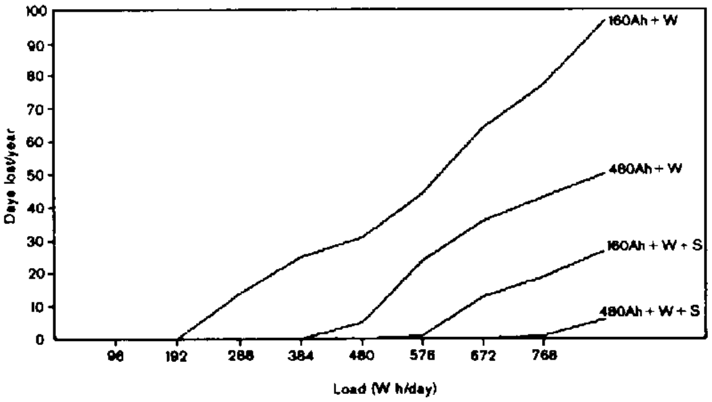


Figure 4:* *Battery bank state-of-charge curves (ranging from 0% to 100%) simulated for the Hybrid wind and solar system (top) and the wind only system (bottom) each serving a 768 W.h/day steady load over the year April 1984 to March 1985. Figures at left indicate days lost (ie days with batteries at 0% charge) for the year. The reduced

Figure 5:* *Plot of days lost per year with various systems simulated for a range of continuous loads with the same weather data. Apart from the extraordinary lull in June, loads twice those indicated were sustainable without loss of days.



In practice, the initial trial design has proven robust after a couple of minor additions, such as a regulated 12V input to the motor, and has remained in place without further modification. The panels are 2A, 12V Solar Wind Corporation single crystal panels in series to 24V. Current designs would produce 2.9 - 3.5 A under similar conditions. 36-wafer panels are essential to guarantee charging in competition with the windmill. Notice from fig 1 that tracking produces two types of performance enhancement. The lateral reflectors boost performance by 1.4 - 1.5 throughout the day. The tracking mechanism, by contrast, spreads the peak output over most of the day. It also causes the reflectors to remain correctly aligned. Combined effects are as follows :

TABLE 1

	Integral	Relative Output
(a) Non-tracking	$2/\pi = 0.6366$	1
(b) Tracking	0.85	1.33
(c) Tracking + Reflectors	$1.4 \times 0.85 = 1.19$	1.86

The Combined System :

If you started out with wind, as I did, you would find that including solar power will give you a much more even performance, and the summer sun will give you a steady output, sufficient, for example, to maintain a small refrigerator. On the other hand, if you started out with solar, you would find a qualitative jump in the grunt of your supply on windy days which makes a whole new set of activities possible. On sunny calm days, or any breezy day the system keeps charging. The only lull is in the centre of a low when there is rain and no wind. The combined system has the T shaped characteristics of a typical domestic supply in which routine demands such as lighting are complimented by specific projects and activities which are intermittently heavier.

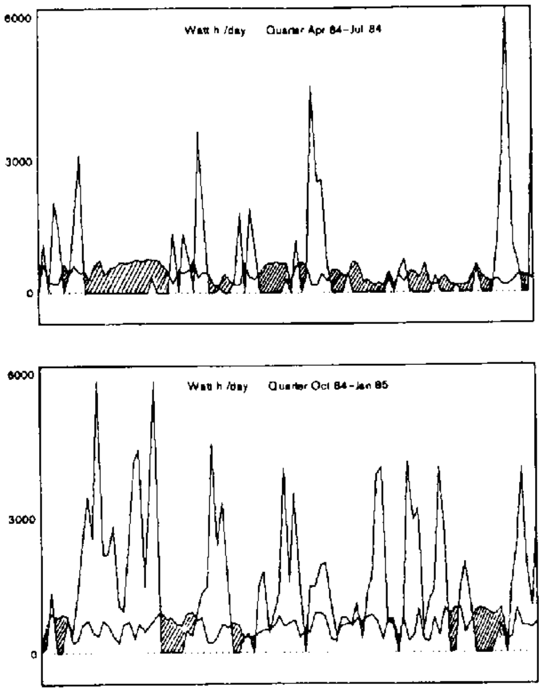


Figure 3: Wind and solar output, showing periods (shaded) in which solar output provided continuity.

The wind and solar systems are connected in parallel. Output is regulated by a 555-based pulse-width modulated 1000 Hz square wave regulator amplified by power transistors and dumped through a shunt. The design ensures transistor saturation and prevents transistor overheating. A hysteresis-type design which cycles the batteries to a higher voltage and then temporarily goes into full shunt is an alternative. A diamond of Lucas DC11 batteries (160 A/h) has provided a low cost 24V storage system. Charge parity between the parallel pairs has been well-maintained over 6 years, and the batteries have shown no sign of deterioration of function.

Because the windmill is optimally sited 300m from the house along with the batteries, the solar unit has had to be installed beside the windmill in a moderately exposed site. Occasional wind disturbance has occurred when the unit has been left idle and in fixed position for a few months, but when active, tracking corrects such errors. The house supply is via a 240V square wave inverter. This is essential, both to ensure efficient power transmission and to enable the use of the full spectrum of electrical devices. The inverter has proven itself by remaining intact and functioning both through dead shorts from insulator breakdown in the supply cable and through a bizarre disconnection of the batteries in a gale which caused the explosion of every electrolytic capacitor in the circuit. Superior inverters such as the TRACE 2 KW inverter enable the intermittent use of heavy machinery such as an automatic washing machine or microwave oven. The inverter is operated from the house by remote control using the third wire of the 3-core underground supply cable and filtering in a DC current on the neutral. This includes a remote voltmeter which tells an amazing amount about the state of the supply, given some experience. Remote control permits zero inverter drain during periods of non-use, the dumping of excess power into low priority activities such as a cooler, and automatic activation on demand. Solar energy couples well to refrigeration as peak demand coincides with peak supply. Low consumption thermocouple cooling panels are now on the market.

In my application a 300W inverter has proved ample, running lighting, computer, television, sewing machine, power tools, and a small refrigerator. The domestic system also includes coupled solar and wood stove water heating and a gas stove and refrigerator. While heavy machinery such as a washing machine has a confined total load over a 15 minute cycle, I have found conventional refrigeration technology a demanding drain on electricity because it involves 24 hr motor consumption. I have found compact electronic fluorescents such as the Phillips PLC* series invaluable as they combine low demand with tolerance to the spiky transformed square wave supply. As an afterthought, I assembled a small back up petrol generator out of a Briggs & Stratton engine and two 12V car generators wired in series (fields and armatures separately). This proved a zero-cost well-matched system giving a charging rate similar to a good wind. However it is virtually never used.

Performance Models of the System :

To give a good quantitative model of the characteristics of the system, a detailed computer simulation of the wind and solar outputs and sustainable loads was undertaken. Hourly records of sunlight and wind speed and direction were obtained from the Auckland meteorological office covering an entire year. These were then processed to simulate the actual site of the system, which was a more exposed site with a single obstructing ridge, rather than a high point on a rolling inland landscape. The overall wind speed was increased by 10/8.5 but the southerly quadrant was reduced to 2/5 of this value, resulting in an identical total flux but with a modified distribution. The wind output cut in at 9 knots and rose linearly to a maximum of 360 W at 30 knots. This coincides reasonably closely with SOMA's specifications for its current 300W model and underestimates the 500W output. The wind data was taken at 6 hr intervals to model the rise of the sea breeze to a maximum at noon. The hours of sunshine were taken daily and composed into 1/4 output during cloud and full output during sun.

The year included both windy periods and calm spells in which solar output maintained continuity, as well as an exceptional lull in mid winter when there was still cloudy weather for almost a month. In fig 3 are shown the wind and solar output over two 3-month periods involving both high and low output. The peaks of wind output are white and the periods of supremacy of solar output are shaded. During the high output period, solar output is dominated by many high peaks of wind, while in the low output period the solar output has ensured continuity of supply.

Graphs of the state of battery charge from 0 to 100 percent under an arbitrary constant drain of 768 W hr/day over the year with and without solar support are shown in fig 4. This clearly demonstrates the improved characteristics of the combined system. It should be noted that apart from one exceptional lull, the combined system has stood at full charge for most of the year. Thus the combined system could usually have sustained drains 2.5 times as high as this. In practise the batteries have been subjected to discharge to a cut off at ~18V where the inverter relay disconnects representing relatively complete discharge. The rapid recharging of the batteries by wind and frequent full charge states has compensated for this with no evidence of battery damage.

The long lull was exceptional on a five year time scale, and was in fact the triggering crisis causing me to build the solar installation. The next season was *El niño* with relentless high winds. Note that, despite being a Winter lull there was a moderate solar output as shown in fig 3, sufficient for lighting. A more accurate estimate of the usual capacity of the system is derived by eliminating this lull, which was chosen to illustrate extremes of weather. Generalization of the site to the original one, i.e. rolling hill country inland can be gained by lowering the wind peak heights by about 1/6 and lifting about one peak in four (a small one) to 2.5 times its height. The effect is to reduce the probable length of a lull by about 50% and hence improve steady output of the wind.

An estimate was made of the days lost in the year for four systems (wind alone and wind + solar were tested with two different battery sizes) due to the batteries being in discharge. As can be seen from fig 5, the number of days lost at various loadings is significantly reduced in the combined system. This data included the exceptional lull, so the omission of the 21 - 30 days involved leaves no days lost at 768 Wh/day for the combined system versus around 70 for wind alone. It should be noted that this rather low value is boosted by up to 200% when the wind peaks are taken advantage of.

TABLE 2

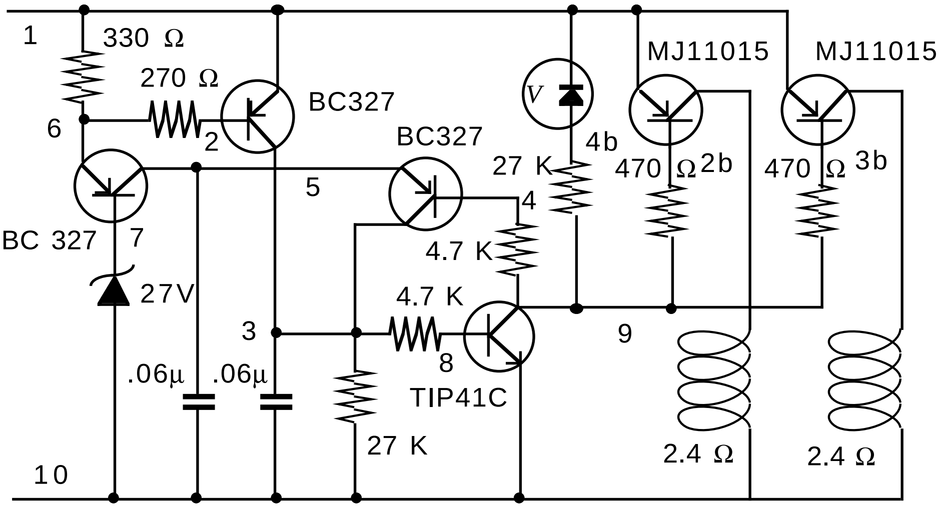
	Cost $N.Z.	Cost $Aus	Integral Output	Steady Output	Combined
windmill	2770	1945	1432	548	990
pole	350	246			
solar	1653.75	1122	1038	675	857
tracking ass.	200	140			
Batt 160 A/h	780	548			
Batt 480 A/h	2304	1618			

In table 2 are the approximate costs of the estimated equivalent system in December 1990 using the current SOMA 300 wind generator and a BP 55 watt (or Solarex 56 watt) panel as equivalents. The SOMA 300 performance curves exceeded the algorithm used in the program at 15 - 25 m.p.h., so a second order adjustment was made. The BP output was scaled up by 3.3 / 2.2 so that the figures hold for what is purchasable today. The steady output has been estimated by taking into account the need to bridge an average lull from full charge in wind and to maintain steady drain under solar input. The integral output has been found by integrating the data over the year and the combined output is the mean of the two. Combined output has been estimated from the data by using the boost in steady output for a fixed number of days lost from fig 5 to estimate the complementation effect. DC11 battery costs were taken at summer discount values, about 2/3 standard retail price in N.Z.

TABLE 3

	Cost $N.Z.(inc GST)	Cost $Aus	Output	Cost Efficiency
s+160	2633.75	1810	857	0.47
w+160	3900	2739	990	0.36
w+s+160	5753.75	4040	2316	0.57
w+480	5424	3809	1432	0.38
w+s+480	7277.75	5111	2446	0.48

In table 3 are shown outputs of various combined systems and the relative cost efficiency scaled to the cost of a simple wind system. A higher value indicates greater efficiency. What is clear is that the combined system at 160 A/h has superior cost efficiency over either single system and close to optimal storage. Again the cost efficiency is deceptive because the spread of output is a better indicator than cost efficiency. Dollar/watt values are also deceptive as the peak watts are 5 - 6 times the steady watts in the case of wind. The wind peaks make possible much higher intermittent use of power for specialized activities. It is obvious from the upper figure in fig 5 that the windmill is contributing a higher input than the solar panels if this availability of intermittent high-power use is included. Over the last 5 years the solar component appears to have improved in cost efficiency compared with the wind, as reflected in current costs and outputs compared with 1985.



Conclusions :

The investment in a dual-input solar-wind generating system has distinct advantages :

(1) Optimal Cost-efficiency, as illustrated in table 2.
(2) A power generation profile that combines well with domestic demand,
    i.e. steady moderate power generation with solid peaks of output for planned uses.
(3) Reliability of supply without the need to operate motor generators.
(4) Pollution-free renewable energy without fossil fuel use as required backup.
(5) Extended battery life through maintenance of steady high charge, combined with rapid recharging.
(6) Elimination of fire risk.

In doing so it replicates the logic of national power distribution systems in a microsystemic setting. Similar considerations can be given to small combined hydro and solar systems, or triple input systems. For example hydro and solar have an obvious seasonal complementation. SOMA are currently marketing a 500W micro hydro turbine which would provide a comparable unit. Unfortunately the site of the current system has too little water to provide an adequate test.

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see also N.Z. Jour. Tech. **1** (1985), 153-158.